# Visualizing Uncertainty for Data Fusion Graphics

*Review of Selected Literature and Industry Approaches*

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# VISUALIZING UNCERTAINTY FOR DATA FUSION GRAPHICS
# REVIEW OF SELECTED LITERATURE AND INDUSTRY APPROACHES

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# ABSTRACT

The objective of this review is to better understand the current state-of-the-art methods for representing uncertainty in sensor-fusion data using graphical, visual displays to inform military decision making. Decision makers in Maritime defence and security often consider many sources of information when trying to develop an understanding of the situation within their area of responsibility. Information from each source has some uncertainty, as does their integrated or "fused" summary result. The purpose of presenting uncertainty is to enhance understanding of where the contact is, has been and will be so that the operator is able to make better decisions about the contact's intent. The scientific literature presents a number of approaches to graphical information visualization that improve comprehension of uncertainty using intrinsic or extrinsic modification of graphical elements. However, little of the existing research shows this understanding results in improved decision making in the Maritime domain. Few commercial vendors of display systems provide uncertainty estimates in their tactical plots and it is not clear whether this feature would be useful to tactical Maritime operators. This report suggests a Human Factors analysis approach to clarify where uncertainty visualization may be useful in Maritime defence and security, followed by recommendations of extrinsic and intrinsic uncertainty visualization techniques that could be used to validate the analysis experimentally.

# RÉSUMÉ

Le présent examen a pour but de mieux comprendre les méthodes de pointe utilisée en ce moment pour représenter l’incertitude associée à la fusion des données de capteurs à l’aide d’affichages graphiques et visuels afin d’éclairer la prise de décision militaire. Les décideurs du domaine de la défense et de la sécurité maritimes doivent souvent prendre en compte des renseignements d’une diversité de sources lorsqu’ils cherchent à mieux comprendre une situation dans leur zone de responsabilité. Les renseignements de chaque source comprennent tous un certain niveau d’incertitude, et il en est également ainsi pour les résultats sommaires intégrés ou « fusionnés ». Présenter l’incertitude permet d’améliorer la compréhension de l’endroit où se trouve le contact, où il a été et où il se dirige afin que l’opérateur soit en mesure de prendre de meilleures décisions au sujet de l’intention du contact. La littérature scientifique présente certaines méthodes de représentation d’information graphique qui améliorent la compréhension de l’incertitude en apportant des modifications intrinsèques ou extrinsèques aux éléments graphiques. Cependant, peu de recherches démontrent que cette compréhension des résultats entraîne une amélioration de la prise de décisions dans le domaine maritime. Un nombre restreint de fournisseurs commerciaux de systèmes d’affichage offrent des estimations de l’incertitude dans leurs tracés tactiques; or, il n’est pas certain que cette fonction serait utile aux opérateurs maritimes tactiques. Le présent rapport suggère d’entreprendre une analyse des facteurs humains afin de déterminer clairement où la représentation visuelle de l’incertitude est utile dans le domaine de la défense et la sécurité maritimes, et il présente des recommandations de techniques de visualisation extrinsèques et intrinsèques qui pourraient servir à valider l’analyse de manière expérimentale.

# 1 INTRODUCTION

This document is one of two contractual deliverables that summarize the work done on W7707-145734/001/HAL "Visualizing uncertainty for data fusion graphics", conducted for Defence Research and Development Canada (DRDC.) The work involves a review of selected scientific literature and a discussion of some current industry solutions for visualizing the uncertainty of sensor data fusion, particularly in the Maritime defence and security domain. The second deliverable, a Microsoft PowerPoint presentation will be provided separately.

A bibliographic database of related literature that was created in Mendeley[1] and Adobe Portable Document Format (PDF) copies of the reviewed documents will also be provided to the client, although they are not contractual deliverables.

## 1.1 Background

Decision makers within the Canadian Armed Forces (CAF) and the Department of National Defence (DND) often consider many sources of information when trying to develop an understanding of the situation within their area of responsibility (AOR). It is generally accepted (although perhaps not proven) that decision makers should be aware of the degree of uncertainty associated with each relevant piece of important information and consider the uncertainty when forming hypotheses or judgements their understanding current operational context.

Martineau and Roy (2011) describe the Maritime defence and security domain where decision makers collect information to infer the intent of contacts operating in their AOR, both civilian and military. Most of these contacts have legitimate reasons for operating in the AOR, but some may be acting for illegal or unsanctioned reasons. Maritime defence and security operators attempt to detect and deal with these undesirable contacts, identifying them from a sea of distractor, legitimate contacts. Data and information used to detect or identify contacts may come from any of a number of sources including ship registries, voluntary reporting or remote sensing in their situation assessment procedures (Lapinski, 2010). Fusing data from these disparate sources to visualize a coherent Recognized Maritime Picture (RMP) can be a challenge.

There may be a large number of contacts in an AOR, but typically there are few if any undesirable contacts. Operators and decision makers attempt to identify undesirable contacts by looking for anomalous behaviour or matching contact characteristics with other intelligence information. Operators exploit various types of technology to collect and manage data on contact behaviour and characteristics, integrating or fusing the data into a more complete picture. Unfortunately, sensors have limited accuracy, may indicate conflicting data or may present irrelevant information due to sensed marine life or interference from the physical environment.

In the past, decision makers have used training and experience to fuse these data manually, but this is a slow process and there is a desire to automate the fusion process as sensor and

[1] http://www.mendeley.com/

processing technologies improve. The human operator will, however, be the ultimate arbitrator in the information fusion process for the foreseeable future. This raises concerns about how any uncertainty that is associated with the fused information should be presented to the operator in order to promote understanding and lead to appropriate decision making.

## 1.2 Objective

The objective of this review is to better understand the current state-of-the-art methods for representing uncertainty in sensor-fusion data using graphical, visual displays to inform military decision making.

The work is intended to summarize the current state of the art in visually representing data-fusion uncertainty, integrating available information and interpreting the results to help direct future research on the Human Factors element in developing the RMP despite inaccurate, incomplete or contradictory data.

## 1.3 Scope

The statement of work was focussed on understanding how to effectively present the uncertainty of temporal-geospatial data associated with a contact. The purpose of presenting uncertainty is to enhance understanding of where the contact is, has been and will be so that the operator is able to make better decisions about the contact's intent. During the project kick-off meeting, DRDC and CAE restricted the scope to how uncertainty in the coordinates (latitude, longitude and altitude or depth) of a contact that are derived from the fusion of data from multiple traditional sensors over a period of time can or should be indicated on an electronic tactical display, particularly in a Maritime defence and security context. This narrower scope was found to be too restrictive during the literature review and so it was broadened to consider visualization of geospatial uncertainty associated with Maritime contacts regardless of the source of the imprecision.

This scope of work does not include certain types of data uncertainty, such as self-report of cargo manifest, nor does it include of the inference and decision making processes that might incorporate uncertainty. The automatic fusion algorithms that generate information presented to the operator are not considered here other than to note that this processing of sensed data will give rise to information that has some associated uncertainty. The client also indicated that they were specifically interested in visual representation of information rather than alternative forms such as auditory or tactile displays, so the bulk of the work is directed towards uncertainty visualization on dynamic, computer-generated, visual displays.

# 2 LITERATURE REVIEW

## 2.1 Method

Searching the literature was largely conducted using online, internet sources using Google and Google Scholar search engines with keywords derived from the statement of work. Relevant documents were downloaded immediately if available, but a few documents were obtained through electronic library access available to CAE and one document was obtained by the client through the DRDC library. Other documents were retrieved from academic institutions and several were obtained from ResearchGate[2]. Additional references were retrieved as recommended by contacted authors in the field or when identified from citations in articles during the review process.

A large number of PDF documents were identified and retrieved (more than 500). The retrieved documents were catalogued using Mendeley[3] bibliographic reference manager using Mendeley's document import capability. This automated process, while not perfect, saved considerable time organizing the documents. Corrections to the automatically populated citation information were made manually as the errors were encountered. The catalogued documents where then prioritized for review as described below.

### 2.1.1 Constraints

The short duration of this project meant that there was insufficient time to physically access public or academic library holdings. Only documents that were readily and freely available electronically were considered; there was no budget for purchasing documents from journals.

### 2.1.2 Sources and Resources

The Defense Technical Information Center[4] (DTIC) was a valuable repository of information. A number of documents were also obtained from the International Society of Information Fusion[5] (ISIF).

Two working groups were found that are relevant to sensor fusion and its application. The Evaluation of Technologies for Uncertainty Reasoning Working Group[6] (ETURWG) and the Canadian Tracking and Fusion Group[7] (CTFG) both have active topic areas involving research in the sensor-data visualization domain and include uncertainty visualization as an area of interest.

The Science and Technology Organization (STO) of the North Atlantic Treaty Organization (NATO) has panels with technical working groups that are interested in sensor-data visualization, notably the following:

[2] http://www.researchgate.net/
[3] http://www.mendeley.com/
[4] http://www.dtic.mil/dtic/
[5] http://www.isif.org/
[6] http://eturwg.c4i.gmu.edu/
[7] http://www.ctfg.ca/

- Centre for Maritime Research and Experimentation (CMRE)
- Human Factors and Medicine (HFM)
- System Analysis and Studies (SAS)
- Sensors and Electronics Technology (SET)

Several relevant NATO STO (and the former Research and Technology Organization, RTO) documents were retrieved during the literature search.

There are a few journals that seem particularly relevant to the broader sensor-fusion visualization domain:

- Information Fusion: http://www.journals.elsevier.com/information-fusion/
- Journal of Advances in Information Fusion: http://www.isif.org/journal
- International Journal of Image and Data Fusion: http://www.tandfonline.com/loi/tidf20#.VOs_KS4TQgA

There are numerous other journals that deal with geo-spatial and temporal visualization as part of a more general mandate, particularly for researchers interested in scientific information visualization (IEEE SciVis) or information visualization (IEEE InfoVis) as well as general perceptual and cognitive scientific journals.

### 2.1.3 Participant Matter Experts

Several researchers in the field of information visualization were contacted and asked to recommend documents relevant to the literature review.

Dr. M. Riveiro[8] has published numerous reports and conference papers that address the issue of visualization within Maritime defence and security domain, including the effects of uncertainty. Dr. Riveiro recommended several documents for review.

Dr. A. Bisantz[9] from the University at Buffalo recommended a copy of a similar review that she had conducted for the Oxford Handbook of Cognitive Engineering, which was obtained by the client for the current review.

Dr. E. Blasch (formerly with DRDC, now at Wright Patterson AFB) recommended some recent DRDC reports that were retrieved.

Dr. A-L. Lapinski from DRDC was contacted indicating that the most interesting results of previous work were PROTECTED B and not generally available.

[8] maria.riveiro@his.se, http://www.his.se/om-oss/Organisation/Personalsidor/maria_riveiro/Publikationer/
[9] bisantz@buffalo.edu, http://www.eng.buffalo.edu/~bisantz/

The following researchers replied, however, the topic area was not in their direct area of expertise so they were not able to provide specific advice:

- DR. M. Friendly, York University
- Dr. S. Carpendale, University of Calgary
- Dr. F. Taylor, Carleton University

### 2.1.4 Document Prioritization

Two DRDC-sponsored reviews of the visualization literature had been conducted previously (Davenport & Risley, 2006; Davenport, 2009) so preference was initially given to more recent documents while not totally excluding earlier works. These two reviews were included in the current review as well as several other relevant DRDC reports.

The first pass at prioritizing the retrieved documents was based on titles looking for keywords and synonyms that were based on the tasking objective. No strict set of keywords was used. The papers were categorized as High (242), Medium (131) or Low (142) “title-relevance”. The 242 High title-relevance papers were too many to review in the time available so a second prioritization step was implemented.

The second pass reviewed the abstracts of High title-relevance and 15 additional papers to assess each paper’s “content-relevance”. These were also categorized as High (112), Medium (65) or Low (80). The 112 High content-relevance papers were still too many to review so a selection of papers from the list was made.

The selection of papers to review was based on documents that had high title and content-relevance, focussing on prominent authors and previous DRDC reports. Particular attention was paid to those documents that included a survey of the literature or that contained empirical evaluation of techniques. The authors that were highlighted because of their prominence in the literature or who had written relevant DRDC reports were: Potter, Pang, Riveiro, Blasch, MacEachren, Bisantz, Matthews and Lapinski.

During the review of the selected papers, additional promising reports were identified and added to the list of available documents. Several of these documents were subsequently reviewed resulting in a final count of 25 papers reviewed in detail while a number of others were accessed to verify or incorporate specific details cited by other authors.

## 2.2 Literature Review Results

Brown (2004) observed that there are a number of ways to indicate uncertainty or to distinguish between levels of uncertainty, but that not all of these approaches are intuitive metaphors that convey that message to operators. MacEachren et al. (2005) note that most approaches for depicting uncertainty in map-based applications build upon Bertin’s visual variables proposed in

1983 for traditional cartography. Bertin[10] originally proposed his visual variables to depict attributes of cartographic objects rather than uncertainty per se, exploiting illustration attributes such as: location; size; grain (texture coarseness, which MacEachren differentiates from texture in general); colour value; colour hue; orientation; shape. User interface design guidance recommends that symbols used to represent data provide a clear, intuitive description of that data, including how it varies. For instance, icon size is an intuitive metaphor for data magnitude; colour is a cultural metaphor that is used to represent classes of data such as friend or foe. In instances where there is no explicit mapping between the visual variable and the data the user must interpret the representation, providing opportunity for misinterpretation. In the current context, using shades of colour to indicate the magnitude of data uncertainty would not provide an explicit, intuitive correspondence between data and symbol as colour is unlikely to be considered an ordered set despite its dependency on light wavelength.

Brown (2004), MacEachren et al. (2005) and a number of other authors have noted that uncertainty can be represented by an intrinsic indicator, such as a change to the data icon's (also referred to as "sign-vehicles") shape, colour or transparency. Alternatively, uncertainty can be represented by an extrinsic indicator, such as additional graphs, an associated glyph or an overlay that leaves the primary data icon unchanged, providing uncertainty information alongside the primary data.

Riveiro (2007) cites some general advice provided by pioneers in information visualization, notably Tufte and Chambers. Riveiro suggests that designers should strive for a high data-to-ink ratio to convey the greatest amount of information in the smallest space (Tufte's Graphical Excellence) while ensuring that the representation does not perceptually distort the data (Tufte's Graphical Integrity) by presenting it in context and by applying labels judiciously to resolve ambiguity. Riveiro reiterates Chambers advice to display information in a salient manner using simple patterns that draw attention at a level commensurate with the information importance – in other words, design primarily with the user in mind, not the display technology. Amar, Eagan and Stasko (2005) go further, observing that the objective of the visualization is not to display the data per se but to support the analysis of the data. Amar et al. stress that there needs to be a much stronger connection to the user goals, both for high-level and low-level tasks, as advocated in Annett's Hierarchical Task Analysis (Shepherd, 2000).

The results of the literature review will be grouped into intrinsic and extrinsic techniques for representing data uncertainty, particularly temporal-geospatial data. Each of these categories has additional subcategories of methods. Other information that is relevant to visualizing information in the Maritime defence and security domain, but not directly addressing uncertainty visualization, is presented in Appendix A.

### 2.2.1 Intrinsic Techniques

Intrinsic data representations techniques include using position, size, brightness, texture, colour, orientation, shape, border (thickness, texture or colour), blurring or transparency. As previously noted, intrinsic methods are differentiated from extrinsic representations because they alter the primary data symbol itself, whereas extrinsic representations add to the primary data symbol.

[10] http://www.infovis-wiki.net/index.php?title=Visual_Variables#Jaques_Bertin

Some of these intrinsic symbol attributes are more applicable to indicating the primary data rather than its uncertainty.

The intent of intrinsic techniques when representing data uncertainty is largely to indicate that some uncertainty with the primary data is present rather than the magnitude of the uncertainty, although some authors have attempted to do both as will be described below. In the specific example of contact location icons, intrinsic symbol modifications would not directly indicate the extent positional uncertainty beyond the nominal symbol location. This is often done to reduce clutter that would obscure other map features or symbols. MacEachren et al. (2005) note that colour hue, colour value and texture are common methods of indicating uncertainty of static data in cartography.

#### 2.2.1.1 Transparency and Saturation

MacEachren et al. (2005) summarize three intrinsic methods for depicting point data uncertainty (such as the location of a vessel on a map.) A reproduction of the approaches is presented in Figure 2-1, shown with uncertainty increasing from left to right. The top scheme, Colour saturation, attempts to depict increasing uncertainty by reducing the saturation level of the symbol fill, achieved by increasing the gray content of the symbol fill colour. The middle scheme, Contour crispness, attempts to depict increasing uncertainty by reducing the crispness of the symbol boundary. The reproduction shown here is a poor approximation of the original figure with fuzziness replaced by concentric circles of lighter shades of fill. The bottom scheme uses MacEachren's fog metaphor where the increasing opaqueness of the inner circle corresponds to greater uncertainty. In MacEachren's technique shown in Figure 2-1, symbol size does not change with uncertainty, so the intrinsic visualization concept shown here is distinctly different from extrinsic techniques such as the threat-rings used in current CAF Maritime tactical displays.

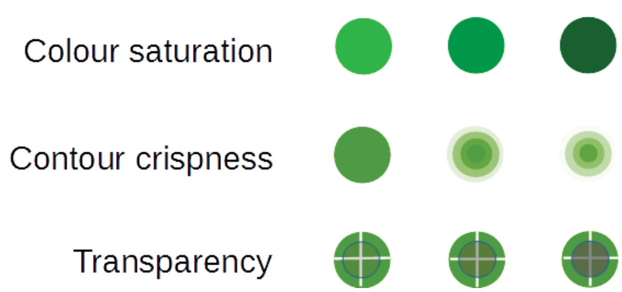


**Figure 2-1: Location Uncertainty Indication. Symbol uncertainty increases from left to right.**
**Image redrawn based on the original image in MacEachren et al. (2005)**

MacEachren et al. (2005) go on to describe some other authors' approaches, such as Drecki's icon opaqueness, where increasing uncertainty was depicted by increasing opaqueness, which would obscure detail under the icon. Another is Pang's (2001) use of glyphs for visualizing uncertainty within flow fields. Although Pang's application was extrinsic, the concept is extensible to a discrete object symbol, where the base icon shape is distorted or augmented (forming a compound symbol) to denote uncertainty. The use of visualization in distributed,

continuous phenomena (such as land use, flow fields, weather, etc.) is a common technique for researchers using geospatial data (population distribution, agriculture, weather, et cetera.)

Bisantz (2013) notes that different colours can be used as primary data indicators, such as Pfeifer's use of colours to visualize robotic machine learning. Pfeifer represented different classes of objects by different colours, as is also done in CAF tactical plots, and then used brightness to indicate belief about the certainty of an object's location and saturation to represent the certainty about the object's presence.

Bisantz (Bisantz, Marsiglio, & Munch, 2005; Bisantz, 2013; Finger & Bisantz, 2000) reported on a series of studies using a symbol-fill strategy to indicate object classification uncertainty. They compared the fill techniques to linguistic indications (numerical percentages, descriptive verbal labels) and an arrow icon with varying sharpness. They applied textures comprising randomly distributed mixtures of red and green squares where the proportions of each colour were proportional to the probabilities that the contact belonged to each of two categories. The results indicated that when the graphical icon intrinsic properties were degraded proportionally to the uncertainty, decision makers were able to make use of that information.

Bisantz (2013) cites one of her earlier studies (Bisantz et al., 2009) that indicated participants could use transparency, saturation and brightness to rank order symbols but that hue was not a reliable indicator. In this same study, Bisantz used the brightness of the symbol to characterize the recency of the data; however, participants became confused about the correspondence between darkness of the icon and recency of the information, with some participants adopting opposite interpretations from other participants. A follow up study suggested that participants were significantly influenced by contrast between the icon colour and the display background than by the absolute level of saturation of the symbol colour.

Bisantz (2013) cites another of her studies (Bisantz et al., 2011) in which transparency was used to graphically indicate uncertainty about objects both with and without explicit indication of the associated numerical estimate of the uncertainty (see Figure 2-2). Participants seemed to adopt different strategies when transparency was used even if the numerical value was also presented. Better scores were obtained when object uncertainty was indicated using transparency regardless of whether the numerical probability was presented. Mental workload did not vary significantly with display conditions (although it was somewhat higher when participants could toggle the display of uncertainty information, presumably due to the additional interaction with the display when hiding or revealing information.) Participants reacted sooner and with less evidence when they were presented with the uncertainty information graphically compared to when information was only presented as the primary data icon that could only change to indicate the highest probability contact. Presenting the associated numerical uncertainty value affected the participant performance somewhat, leading to more conservative decisions than when the numerical value was not presented.

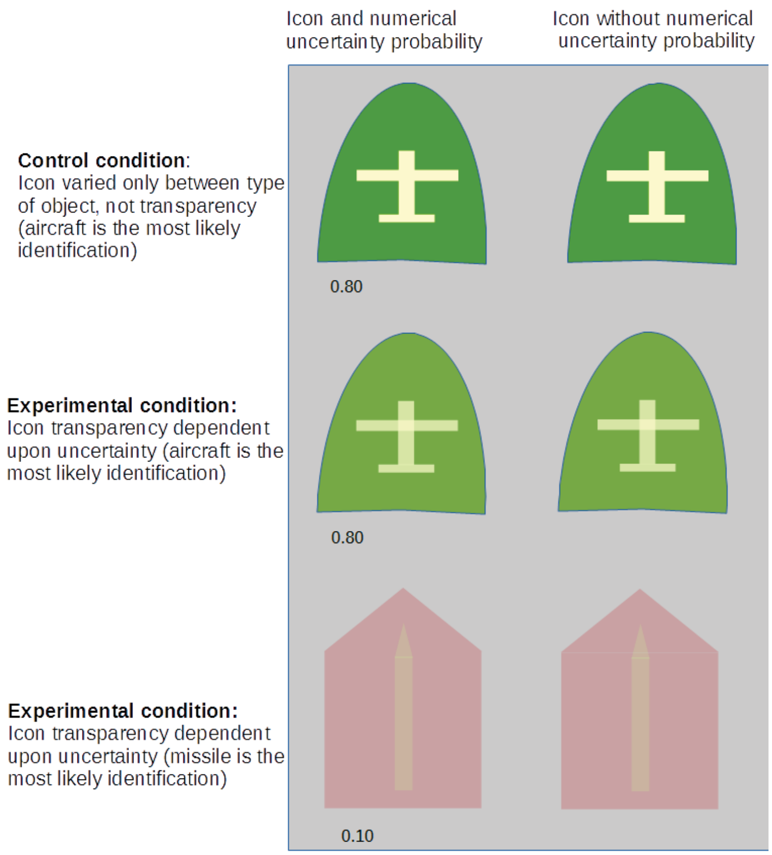


**Figure 2-2: Example of using icon transparency (on a gray background) to demonstrate uncertainty for 2 object types both with and without numerical uncertainty. Image redrawn based on the original image in Bisantz et al. (2011).**

Riveiro (2007) cites some authors[11] who offer the opinion that varying colour saturation is not an effective means of depicting uncertainty and others[12] who feel that the evidence supports lightness to be the more intuitive representation method when using intrinsic colour attributes to indicate uncertainty magnitude. However, it is unclear whether the differences in opinion among researchers stem from differences between studies or if the benefits of visualizing uncertainty differ so much between tasks that generalizing observations to other contexts may be premature, requiring additional, qualifying constraints.

[11] M. Leitner and B. P. Buttenfield, "Guidelines for the display of attribute certainty," Cartography and Geographic Information Science, vol. 27, no. 1, pp. 3–14, 2000.
Schweizer and Goodchild (D. Schweizer and M. Goodchild, "Data quality and choropleth maps: An experiment with the use of color," in Proceedings, GIS/LIS, vol. 2, 1992, pp. 686–699.
[12] B. A. Jiang B. and F. J. Ormeling, "Some perceptual aspects of colouring uncertainty," Advances in GIS Research II, pp. 477–490, 1996

#### 2.2.1.2 Blurriness and Animation

As noted in the preceding section, the use of visualization in distributed, continuous phenomena (such as land use, flow fields, weather, etc.) is a common technique for researchers using geospatial data. MacEachren notes that authors have used animation, such as rapidly changing colours, to indicate uncertainty.

Bisantz (2013) cites studies of icon blurriness (Bisantz et al., 2005; Finger & Bisantz, 2000) that indicate participants are capable of distinguishing and ordering images among a sequential range of distorted icons. Finger and Bisantz (2000) investigated the use of icon pairs that had culturally semantic connotations as well as abstract figures but did not find any significant effect during identification or rank ordering performance. In the culturally semantic, iconic pair condition, they used either a (happy-face, sad-face) or a (dove-of-peace, skull-and-crossbones) icon pair to indicate (friendly, hostile) objects. In the abstract pair condition they used either (∩, Λ) or (O, X) symbols for (friendly, hostile) objects. They used squares coloured either green or red to represent friendly or hostile objects respectively in the combined abstract-iconic condition.

Finger and Bisantz (2000) observed that the time to identify an object did not depend upon on the type of icon used, suggesting that participants quickly learned to associate meaning even to abstract symbols, although there were only two categories of objects (i.e. friendly or hostile). The subsequent studies reported in Bisantz et al. (2005) extended the investigation of Finger and Bisantz by also including colour texture variability, verbal uncertainty labels and numerical estimates of uncertainty in a decision making task. Performance was found to be largely unaffected by the method of representing uncertainty although there was an interaction whereby decision time decreased in the higher uncertainty conditions when some indication of the uncertainty was presented.

Brown (2004) proposes the use of animation in the form of vibrating features to convey the concept of temporal uncertainty. Brown suggests that blurring is an effective metaphor when trying to depict uncertainty, achieved by retaining many of the gross object features but eliminating finer features and smearing the corresponding details. By introducing a vibrational component to objects, the image features can oscillate to indicate uncertainty of location over an area. Brown notes that Tufte advises against using vibration in displays as it can be annoying to the operator and this is reiterated in MacEachren et al. (2005). However, Brown feels that there may be applications were it is appropriate, particularly when it is important to attract the operator's attention to the fact that some aspect is uncertain or requires further inspection.

Brown (2004) indicates that oscillating between colours or varying intensity are effective means of demonstrating dynamic visual effects, even with stationary objects. Vibrating textures, high frequency changes in contrast, hues, luminance, etc., can be used to create a shimmering effect to highlight that there is some uncertainty. Such an approach is probably not effective at denoting the magnitude of the uncertainty, but should be effective for indicating categorical ranges (e.g. high, medium, low). Brown discusses this approach in the context of terrain maps, but similar methods could be conceived for object temporal-spatial uncertainty. Animation approaches can be applied to object fill or to border shape.

### 2.2.2 Extrinsic Techniques

Extrinsic techniques of representing information are approaches that leave the primary data icon unchanged but add to it, creating a composite image. For example dials, thermometers, arrows, bars, pie charts, graphs, complex objects, glyphs, et cetera may be used to display additional information or to represent that additional information is available. Similar to intrinsic techniques, some extrinsic techniques are better suited for representing uncertainty than others.

#### 2.2.2.1 Descriptive Labels

Descriptive labels are added alpha-numeric notations associated with the primary data icon that provide an indication of either the numerical value or a verbal, linguistic description of an contact's uncertainty. The studies of Bisantz et al. (2005) reported in section 2.2.1.2 also included extrinsic representations of uncertainty, labelling icons with either a numerical probability or a corresponding verbal descriptor (e.g. 'Very unlikely', 'Uncertain', 'Better than even', et cetera.) Performance in a decision making task did not depend substantially on whether uncertainty was indicated extrinsically or embodied in the icon intrinsically.

#### 2.2.2.2 Animation

Brown (2004) cites MacEachren (1992) who suggests using iconic pairs for representing object information: a static icon for the primary data coupled with a secondary icon for secondary data (e.g. uncertainty) that may be animated. Brown also cites Kardos et al. (2006) who applied blinking polygons and colours (among other techniques) to highlight uncertainty in area data shown on a map. The results suggest that blinking was the preferred technique for conveying uncertainty in the task studied; however, this preference may be significantly dependent upon the task, notably the number of simultaneously blinking objects and the task duration.

#### 2.2.2.3 Glyphs

Pang, Whittenbank and colleagues (A. T. Pang, Wittenbrink, & Lodha, 1997; Wittenbrink, Saxon, Furman, Pang, & Lodha, 1996) define a glyph as "…a geometrically plotted specifier that encodes data values", although a glyph could equally well be described more generally as an icon or symbol used to convey meaning. We will primarily focus on extrinsic glyphs in this section, although the definition and the examples overlap with intrinsic methods, particularly varying shape or colour. However, a glyph can also be an addition of a symbol to the primary data icon, such as the threat rings that are currently applied to contact icons on tactical plots. In one of the examples offered, arrow glyphs were used to indicate ocean current primary data of direction (arrow direction) and speed (arrow length). They encoded uncertainty of these primary data by varying the width of the arrows and the number of arrow heads. They note that thicker (uncertain) arrows are more salient, which may divert attention inappropriately, but that intrinsic variation of colour brightness may be used to counterbalance this effect.

Bisantz (2013) notes that numerous researchers have used rings or ellipses to characterize location uncertainty, notably the pioneering work by Andre and Cutler (1998). This technique is similar to the use of contact threat rings or submarine location uncertainty ellipses in current

tactical displays. Andre and Cutler (1998) studied three approaches for depicting location uncertainty and three approaches for depicting heading uncertainty as shown in Figure 2-3.

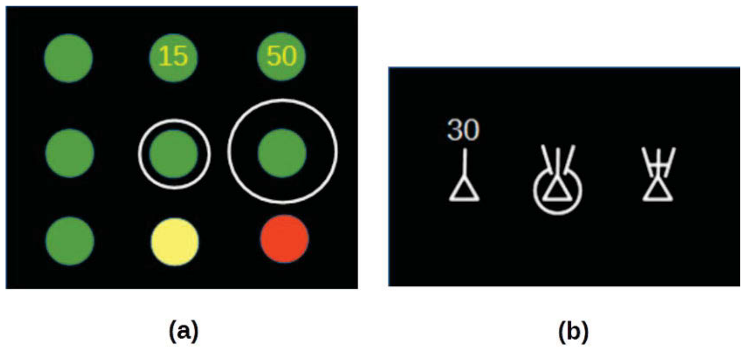


**Figure 2-3: Extrinsically depicting uncertainty associated with the primary data. (a) Increasingly uncertain location from left to right; (b) Various heading indicators with a single uncertainty value of 30 degrees. The location uncertainty colour coding method (lower row of figure a) is actually classified as intrinsic. Images redrawn from descriptions and original images in (Andre & Cutler, 1998).**

In Andre and Cutler's (1998) navigation-task experiment, participants had to navigate an icon representing their own-ship around a moving object to avoid collision while minimizing course deviation. The nominal location of the object was indicated by a point-location icon that was common to all conditions. The uncertainty of the location of the moving object was indicated in one of three ways, two graphical and one textual as illustrated in Figure 2-3a. The colour coding method (lower row of Figure 2-3a) is actually classified as intrinsic.

In this first experiment, they observed that although representations produced fewer collisions than the control condition (point icon only), the explicit representation of the circular area of possibility resulted in the fewest collisions.

In Andre and Cutler's (1998) second experiment, they used simple triangular icons with a heading vector to indicate contacts, similar to tactical plots. Participants were asked to judge hostile intent based on approach behaviour. Uncertainty in a contact's heading was indicated extrinsically, either numerically or with one of two graphical arc representations as shown in Figure 2-3: Extrinsically depicting uncertainty associated with the primary data.

They observed that all of the heading uncertainty indication methods were superior to the control condition of no heading uncertainty indication, but differences among the methods were minor.

Bisantz (2013) cites Kirschenbaum and Arruda (1994) who studied the display of uncertainty in a simulated submarine hunting experiment using ellipses or verbal descriptions to indicate uncertainty of the relative submarine location as it moved across the map display. The control condition showed only the nominal submarine track on the display. Both of the uncertainty conditions were superior to the control condition when predicting range, but there was no significant difference between the uncertainty condition results. Bisantz (2013) also notes that

colour brightness has been used by Slocum and colleagues to map water availability, with bright coloured areas being more certain than dark coloured areas. Such an approach could also be applied to area glyphs to denote locational uncertainty, similar to that used in submarine location uncertainty ellipses currently used on tactical displays.

In a subsequent experiment, Kirschenbaum et al. (2013) manipulated uncertainty displays, presenting the uncertainty of the nominal primary data

- numerically, with uncertainty presented in a table above a graphical plot of the nominal object location
- graphically, showing spatial extent of the probably nominal object location on the graphical plot
- a combination of tabular and graphical indications of uncertainty of the nominal object location

Kirshenbaum et al. (2013) found that experts were more accurate than novices when the uncertainty information was presented numerically in the table, but displaying the location uncertainty graphically improved performance, allowing novice performance to approach that of the experts. There was no significant difference for the time to make a decision in any of the conditions.

Bisantz (2013) cites Schaefer et al. (2004) who used an Air Traffic Control (ATC) scenario to assess the effectiveness of uncertainty bubble overlays for two prototype decision support tools being investigated by Eurocontrol. The Potential Problem Display (PPD) displays predicted conflict between aircraft in a horizontal, plan view while the Vertical Assistance Window (VAW), which displays vertical flight profiles (see Figure 2-4). These tools were presented in addition to the traditional plan view of the controller's assign airspace responsibilities. They observed that ATC operators found the concept of uncertainty foreign and the prevailing opinion was that displaying uncertainty required extra effort while not providing much benefit.

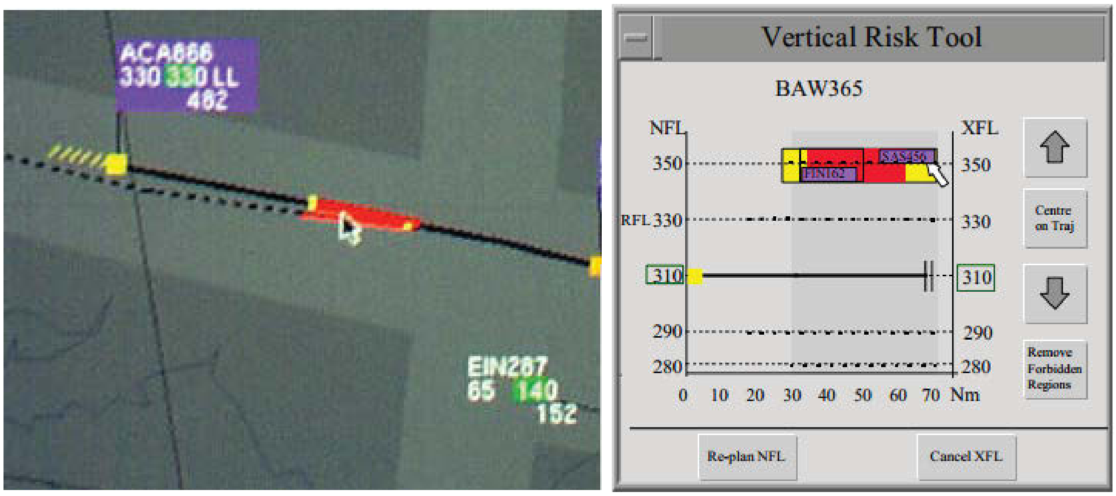


**Figure 2-4: PPD and VAW from FACTS 1b Trial.**
**Reproduced from Whysall (1998). © EUROCONTROL**

Riveiro et al. (2014) conducted a study using a simplified tactical plot in a Maritime defence and security decision making scenario with military ATC officers. The control condition contained no indication of data uncertainty, although the uncertainty was randomly manipulated during all the trials. In the control condition, contact state data for altitude, bearing, range and speed were presented for the selected contact in graphs as a function of time-late, each similar to the top graph on the left side of Figure 2-5. Geographical location with a velocity vector was presented on a map display for each contact, similar to single contact shown on the right side of Figure 2-5 but with only the nominal location, not the uncertainty circle. In the experimental group, uncertainty for the contact state data was presented as in the lower left graph of Figure 2-5 while the tactical plot was as shown on the right.

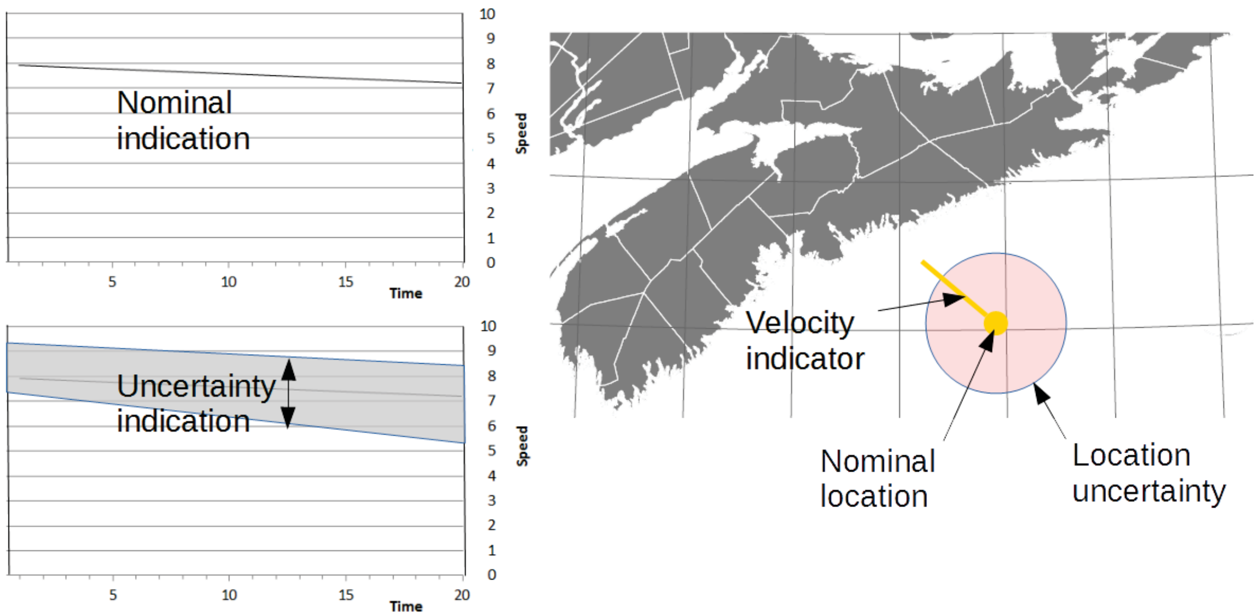


**Figure 2-5: Examples of data presentation for a Maritime ATC task.**
**Image redrawn based on original images in Riveiro et al. (2014)**

The results did not indicate any significant difference in the time it took to make decisions or in the accuracy of those decisions. Participant confidence was also similar between groups. The authors note that null effects such as this are common for experiments involving decision making with uncertainty displays and cite other studies available in the literature. The results did not confirm a study by Stone and colleagues[13] who observed participants' behaviour was more conservative when uncertainty was displayed.

In a subsequent report (Riveiro, Helldin, & Falkman, 2014) extended previous work, using fighter pilots making judgements about contacts employing an automated decision-aid that displayed information fusing recommendations. The experimental conditions included a control (textual data with no automated fusion) and two experimental conditions (automatic contact classification displayed textually; textual classification and graphical values of the sensor data.) Both experimental conditions significantly increased decision time, but there was no significant difference for incorrect classifications. Although there were minor, insignificant differences in the classification and trust ratings, participant opinions suggested that the additional information would have led to greater trust and faster decisions if they had more opportunity to train with the experimental displays, so learning effects likely confounded the manipulations and the conclusions should be suspect.

Lapinski (2010) reports on studies conducted by HumanSystems Inc. and DRDC that assessed two different approaches for data quality representations. The first was carried out by Matthews et al. (Matthews, Rehak, Famewo, Taylor, & Robson, 2008) and used colour (identity indication)

[13] Stone, E.R., Yates, J.F. & Parker, A.M. (1997) Effects of numerical and graphical displays on professed risk-taking behavior. Journal of Experimental Psychology: Applied. 3(4) pp.243-256

and geometry (location and time) glyphs to indicate the precision of the primary data as shown in Figure 2-6. Spatial uncertainty was coded by the number of squares in the horizontal bar (Lego design) or the size of the black dot (Rectangle design) – the smaller the number of squares or circles, the more precise the location was known. Time-late uncertainty was coded by the location of the black dot in the rectangle (Rectangle design) or by the number of squares in the vertical bar (Lego design) – more recent data was indicated by positioning the black dot to the left and moving it to the right to indicate older data while the number of vertical rectangles corresponded to the age of the data.

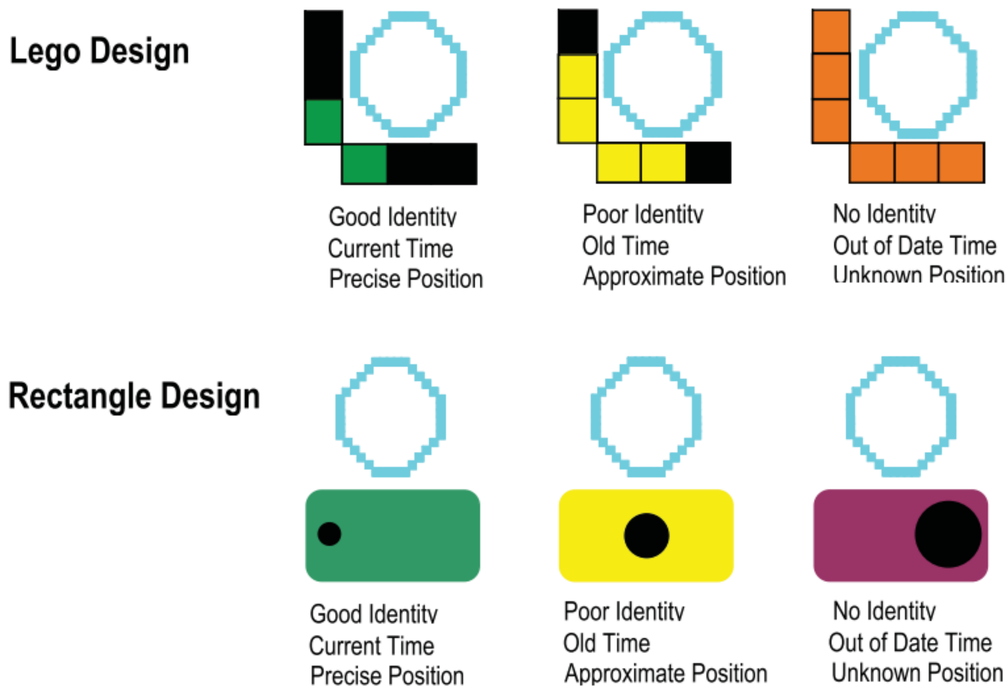


**Figure 2-6: Two methods using colour and geometry in glyphs added to the primary data icon to display uncertainty in the primary data.**
**Image reproduced from (Matthews et al., 2008).**

Analysis of these glyphs in a search task indicated a small but significant advantage for search time with the Rectangle representation compared with the Lego representation but both methods resulted in similar, low error levels (Matthews et al., 2008).

The second approach provided indication of the geographic extent of the sensor coverage uncertainty as shown in Figure 2-7. Although this technique was studied as an indication of sensor coverage, a similar concept could be applied as a secondary contact-glyph to indicate the extent of associated uncertainty of location and time-late. In this approach, light gray or fine grid fill indicated good quality sensor coverage while dark gray or coarse grid fill indicated poor sensor quality. Time-late was indicated by the border attributes, either by colour (with gold indicating old data and green indicating current) or by style (with broken indicating old and solid indicating current).

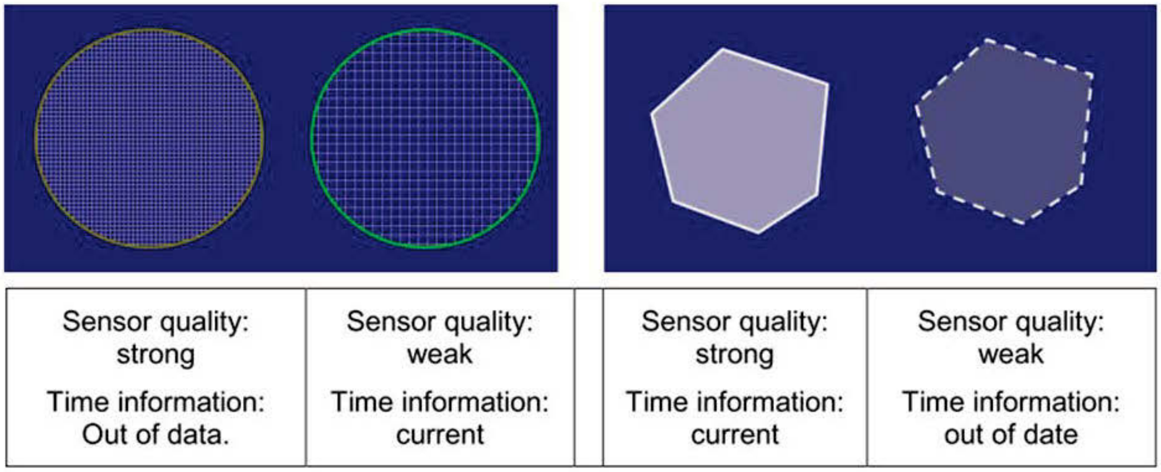


**Figure 2-7: Two graphical methods of indicating sensor coverage and quality. Image reproduced from (Lapinski, 2010).**

Addition of the sensor coverage indicators to the plots with the contact-glyphs of Figure 2-6 did not result in a significant improvement in search time. The difference in search times between conditions with the two sensor coverage approaches was small (0.3 to 0.4 seconds) but statistically significant.

McFadden et al. (2008) cite earlier work[14] using glyphs shown in Figure 2-8, however the earlier work only considered SME preference. McFadden et al. used standard primary data symbols and applied one of two extrinsic glyphs (or alternatively adjusted the primary data symbol intrinsic colour saturation) to indicate data quality as shown in Figure 2-9.

[14] Lockheed Martin Canada Inc. (2001). COMDAT uncertainty trade off analysis. Lockheed Martin Canada Inc., Montreal, PQ. (Power Point Presentation).

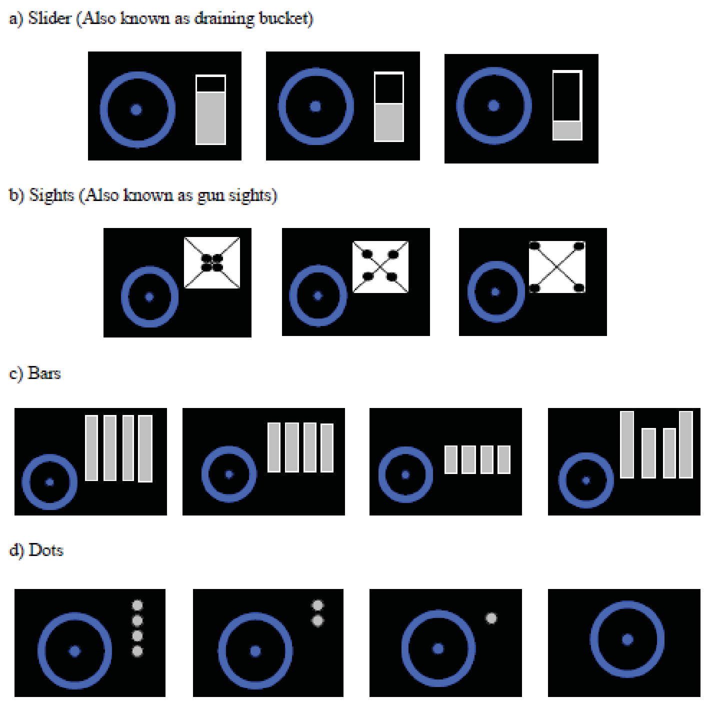


**Figure 2-8: Secondary glyphs used to indicate data quality assessed by Lockheed Martin. Image reproduced from (McFadden et al., 2008)**

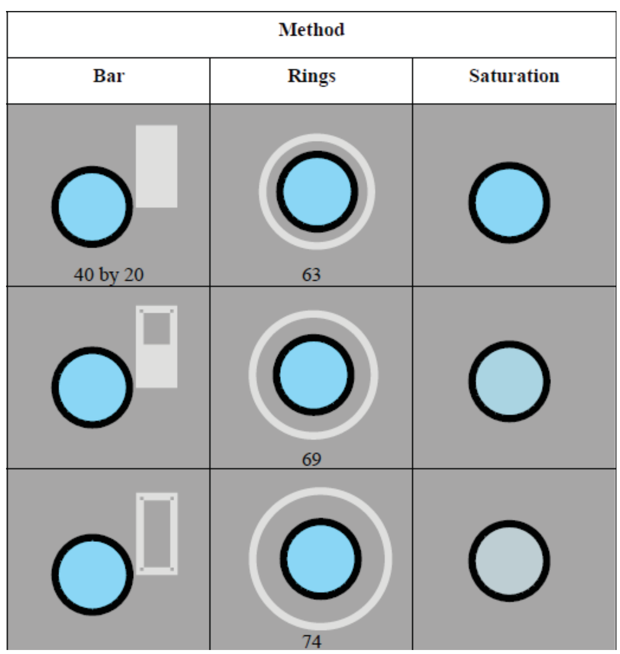


**Figure 2-9: Two extrinsic and one intrinsic methods to indicate data quality. Image reproduced from (McFadden et al., 2008).**

McFadden et al. found that the intrinsic, saturation method resulted in longer search times and poorer accuracy than the extrinsic methods. The extrinsic methods also increased the search time relative to the control condition with no uncertainty indication. In the discussion, McFadden et al. indicate that the bar method seemed to be the most successful of the three methods studied, but that it did result in some response inconsistencies so there may be difficulty differentiating among the uncertainty level indications. The ring method was found to be the least successful, significantly interfering with searching, although the authors speculate that this may be due to an experimental confound of confusion with range-rings used on military displays (the participants were military personnel.)

#### 2.2.2.4 Track History and Projection

Moving contacts add the dimension "time" that may be relevant to the decision maker, carrying geospatial uncertainty over an area rather than at a single position. An example from the civilian domain is predicting the track of hurricanes, as in Figure 2-10, when planning relief efforts.

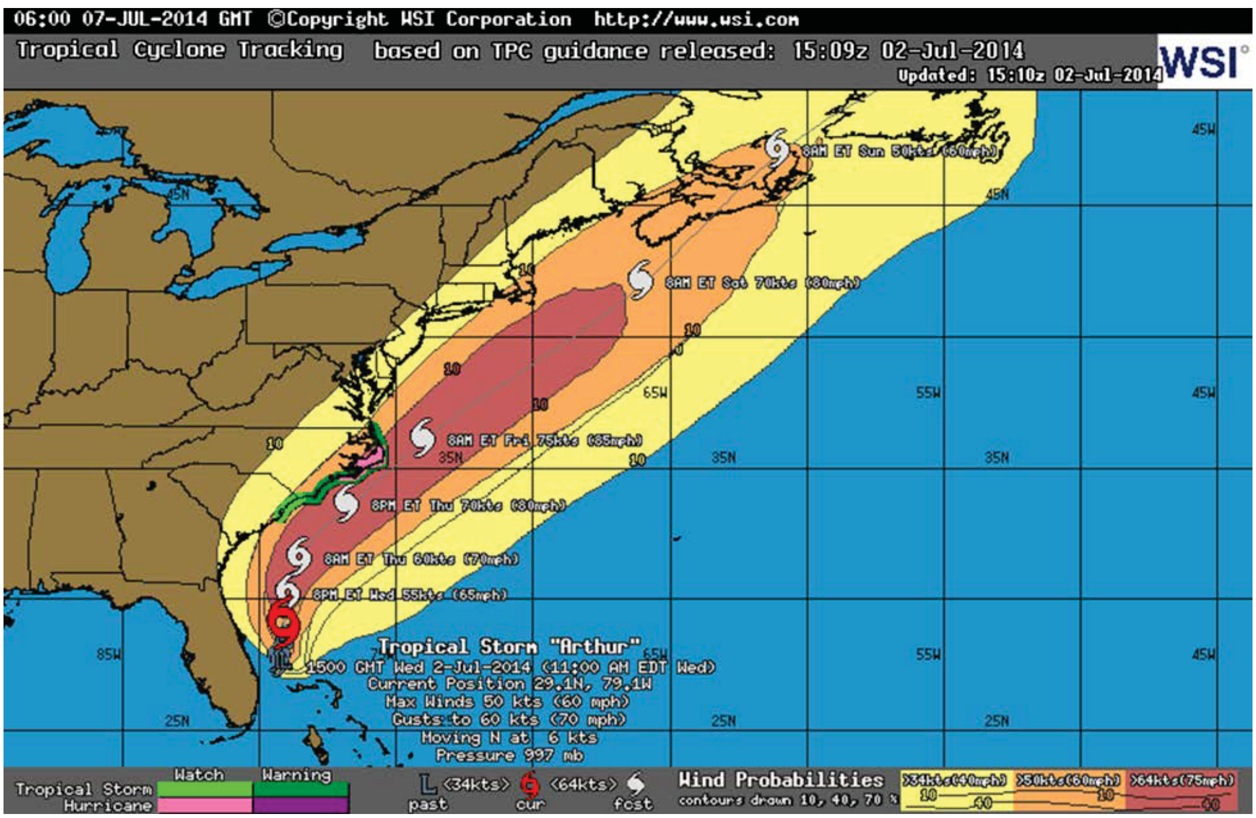


**Figure 2-10: Prediction of the potential track of tropical storm Arthur, 2014. Image retrieved and reproduced from [https://sky7weather.wordpress.com/](https://sky7weather.wordpress.com/)**

Another aspect relevant to Maritime defence and security is the visualization of effects that currents and winds may have on the location of vessels in distress during Search and Rescue (SAR) operations. This suggests that some technique for visualizing spatial uncertainty of data

fused over time would be as advantageous as that from fusing data from multiple sensors for a point location.

Montello (2009) notes that without a detailed understanding of the expert operator's tacit knowledge, designers can fail to adequately support the operator. They provide an example where, when displaying route information, a designer may only show nominal shipping lanes or sea bed topology but may fail to display both; however, a ship's captain may choose a route that safely minimizes distance traveled yet is outside of the normal shipping lanes. Providing the operator with both the shipping channels and the seabed topology may be essential to determining whether the ship is operating legally, if somewhat anomalous, or is pursuing illegal activities. The operator may need to be aware of the rationale behind such observable behaviours, such as a captain's desire to minimize sailing distance, to determine whether a track history demonstrates anomalous behaviour is reasonable and thus probably legitimate.

Bisantz (2013) cites Clausner and Fox (2005) who created a set of visual metaphors for depicting temporal uncertainty of geospatial data, although no assessment of their effectiveness was made. The shapes consisted of regular shapes such as ovals and rectangles oriented along track lines. One example of the visual metaphors is reproduced in Figure 2-11, which, while originally intended to indicate only temporal uncertainty along a timeline, might be adapted to also indicate spatial uncertainty by varying the oval width. In Clausner and Fox's metaphor, solid, linear objects (lines and rectangles) represent certainty while dashed and rounded objects (ovals) denote uncertainty. The vertical lines representing the temporal extent would be omitted if there was uncertainty about the start or end times. The solid oval denotes a fixed event of short duration while the dashed oval occurs over a longer interval and may slide along the timeline due to uncertainty in its specific duration.

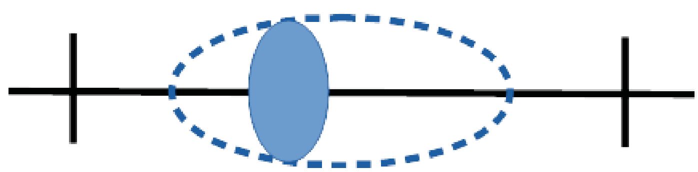

**Figure 2-11: Sample visual metaphors for events happening in time. Image redrawn based on original image in Clausner and Fox (2005).**

### 2.2.3 User Control

Several authors advocated some form of user control over when and how uncertainty is displayed. Some of this may simply be repetition of "common sense" but the opinions expressed by ATC officers reported by Schaefer et al. (2004) supports this perspective. While accommodating uncertainty in decision making may be culturally constrained, the underlying human factors of detection among distractors and information overload suggests that operator control will be an important factor to consider to ensure comprehension (Fewell & Hazen, 2005; Nicholls & Battino, 2003; Vatin & Napoli, 2013).

Riveiro et al. (2014) and Gomez & Chimento (2011) note that many decision making aids fail to provide information that is the basis for recommendations. They recommend that data fission tools be provided to allow the operator to deconstruct the fused information to expose the

contributing data and better understand what the fused information is indicating. This may be particularly true with high level information fusion, but as the number of sensors increases and as fusion algorithms become more comprehensive, operators will need some means to verify and establish trust or recognize when the automation is unreliable.

Bisantz et al. (2011) found that participants performed better when they could toggle between displaying and hiding uncertainty information. Participants seemed to be using the visualization or uncertainty but not the numerical indication of uncertainty as indicated by higher performance scores for the graphical uncertainty condition. The improved performance came with a small cost of slightly greater mental workload, principally in the Physical Demand category of the NASA TLX rating scale.

As noted previously, Amar and colleagues (Amar et al., 2005; Amar & Stasko, 2004) recommend a strong focus on user-centric design with “analytic primacy” as the main consideration driving visualization designs rather than a data-centric “representation primacy” perspective. They challenge Tufte’s admonishment to “above all else, show the data” that, in some respects, is counter to the objective of data fusion, depending upon what is considered as data. Amar et al. feel that this “representation primacy” will not adequately support interpretation but caution that this does not mean a black-box approach (to data fusion) should be adopted. The operator should be provided with “discovery tools[15]”, allowing a “white box” approach that supports effective operator interaction with the presented information to expose uncertainty what is presented and provide a means to understand the implications of the uncertainty specifics.

### 2.2.4 Literature Review Discussion

The literature of uncertainty visualization and the related field of decision making under uncertainty are multidisciplinary and extensive (MacEachren et al., 2005). The literature on multisensory data fusion is somewhat smaller, but still large judging from the number of references returned from Google searches. Restricting a literature review to only Maritime defence and security applications makes the task more manageable, but may overlook many useful papers that deal with visualizing uncertainty for geospatial data generally and other military applications specifically.

MacEachren (2005) notes that "*…(I)information uncertainty is a complex concept with many interpretations across knowledge domains and application contexts.*" Although the current tasking is focussing on temporal-spatial uncertainty of contacts in a Maritime defence and security context, there are a number of levels of information aggregation in developing the Recognized Maritime Picture (RMP), and each level of aggregation may have its own uncertainty visualization requirements.

The techniques of uncertainty visualization reviewed in this project were categorized as either intrinsic (modification of the primary data sign) or extrinsic (addition to the primary data sign.) Maritime RMP displays often use four intrinsic attributes of icons, position, orientation, shape and colour, to indicate primary contact data nominal location, velocity (by means of a vector

[15] After Schneiderman, B. (2002) Inventing discovery tools: Combining information visualization with data mining. Information Visualization, 1(1), pp. 5-12.

add-on glyph) and identification category, with colour and shape used redundantly. While varying these attributes to denote or connote uncertainty may be feasible, effectiveness remains to be determined, particularly as some of these features may become indistinct as the display field of view is increased. Further, there are international symbology standards that may preclude significant modification of the primary data icon. This suggests that secondary data such as uncertainty should be displayed extrinsically, or if intrinsic uncertainty indications are used, there should also be extrinsic indicators that are displayed redundantly.

Pang and colleagues (1997) acknowledged that altering primary data icons to provide secondary information could lead to inappropriate salience. They suggest that designers may want to consider combined techniques, such as counterbalancing icon thickness with decreased brightness to maintain a level of salience that is commensurate with the importance of the information.

Brown cites Ehlschlaeger et al. (1997), suggesting that providing the operator with the ability to control the display of secondary icons or suppressing animation may exploit the attention-grabbing characteristics without unduly annoying the operator. Such an approach may be advantageous when trying to visualize the track history of a contact that is based on intermittent observations. Schaefer et al. (2004) also suggest that if uncertainty is going to be displayed with primary data, it should be available on demand. Cultural and task-demand differences may lead to contexts where the display of uncertainty is counter-productive. For example, if air traffic controllers are unused to thinking about uncertainty, displaying it may create additional workload and confusion during time-sensitive decision making. Schaefer et al. suggest that uncertainty visualization may be more relevant to longer term planning than immediate control and that displaying uncertainty may well lead to overly complex displays – less may be more and it is likely context dependent.

Colour hue is already used as a primary data intrinsic indicator, redundant with shape, for contact symbol borders on tactical displays. This suggests that neither hue nor shape would be appropriate for indicating uncertainty, at least for the symbol borders, as they already have a role conveying information and alteration may lead to misunderstanding of the primary information. Using symbol-fill hue variation to indicate uncertainty would have to be assessed for salience and interference with the primary data indicators. Further, although colour is fundamentally an ordered quantity due to its dependency on wavelength, it is unlikely to be perceived that way automatically suggesting the correspondence between hue and uncertainty would have to be learned, creating opportunities for failure.

Symbol brightness or transparency may lead to inappropriate saliency that distracts the operator even though the literature suggests they may be effective indicators for ordered information such as levels of uncertainty. If these intrinsic characteristics were applied under operator control, however, they may be effective means to quickly assess which contacts require refreshed data. A similar approach might be considered for applying animation.

The extrinsic techniques seem to have the greatest potential for unambiguous representation of uncertainty, although that is not guaranteed. The extrinsic techniques do have the potential disadvantage of adding clutter to the display, so it is likely that they should be used with operator control as well. As threat rings are used as secondary, important contact information on tactical plots, using extrinsic area graphics similar to the sensor area coverage use in Figure

2-7 to indicate location uncertainty may be inappropriate unless it is applied under operator control. Other extrinsic methods such as the Lego or Rectangle methods of Figure 2-6 may provide a compromise between clutter and intelligibility if it is found that continuous display of uncertainty is advantageous. However, there should be clear, culturally semantic associations between the meanings of such glyphs in the applied context.

Intrinsic and, to a lesser extent, extrinsic approaches to representing the extent of temporal or geospatial uncertainty may be somewhat ambiguous as indicated by participants confusing the intended associations in some of the experimental studies. This suggests that a graphical display strategy for depicting uncertainty of primary data should be kept simple if it is symbolic rather than displaying a physical correspondence. In any event, the user interface should allow the user control to display the secondary data optionally or in successive levels of detail to delve deeper to expose the contributing elements.

# 3 INDUSTRY SURVEY

The industry survey was undertaken to understand what is currently done to represent temporal-geospatial uncertainty in data fusion graphics. This survey begins with a short review of ATC tactical displays and then discusses current military standards that are shared among western nations before moving onto specific examples in the Royal Canadian Navy (RCN). The survey then considers private industry organizations who are actively dealing with data fusion and uncertainty.

A traditional keyword search involving various combinations and variations of, graphics, data fusion, geospatial, uncertainty and company failed to indicate industry representatives who are active and dedicated to the development of uncertainty visualizations for data fusion graphics. Instead, industry knowledge was used to enter the participant and, thereafter, the ‘path’ being uncovered was followed.

## 3.1 Air Traffic Control

Air traffic control (ATC) was considered because it uses a tactical situation display (TSD) that is similar to military tactical plots, although the industry uses a different approach to data fusion than seen in military domains. There are two reasons for the different approach: (a) there are fewer sensors being used and (b) the airspace is generally populated by cooperative targets. In ATC only radar (primary and secondary) are being used to plot the location of contacts. Since ATC is generally a cooperative practice, all aircraft in the system are providing identity information, so there are few unknowns and therefore less need for data fusion or associated symbology. The exception is an aircraft that is not providing identification information but these are readily identified by primary radar and tracked as unknown contacts.

At the lowest level, ATC practices low-level information fusion (LLIF) by fusing data from primary radar, Mode A, Mode C and Mode 3. These sensors are all radar based and are therefore highly accurate. Typically the primary radar video is suppressed and replaced by Mode A/C symbols (in practice Mode 3/C are the same). The resulting symbol is intrinsic, as shown in Figure 3-1.

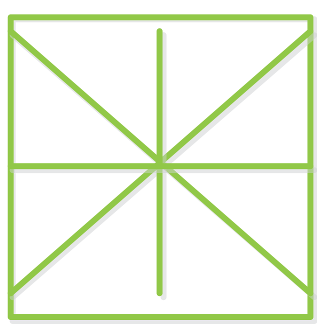

**Figure 3-1: ATC Contact Symbol**

The raw radar return is processed and represented as a square; the ‘+’ in the middle of the square represents Mode A and the ‘x’ in the middle of the square represents Mode C. However,

more modern ATC displays have foregone this sort of symbology due to the high reliability of radar and transponder systems and now instead use small aircraft symbols.

In creating the symbol, sensors that are used are co-located. The ATC system does not fuse data from sensors in different locations, instead adopting a ‘radar mosaic’ approach. In this approach the airspace is divided into ‘tiles’. Analysis is performed for each tile and the best radar source for that area is selected. The system automatically switches the radar source as an aircraft tracks from one tile to another.

## 3.2 Military Standards

The most widespread military standard for graphics is MIL-STD-2525C (DOD, 2008). MIL-STD-2525C describes common warfighting symbology that has been developed using human factors research to eliminate conflicts between symbol sets and allow information sharing between different military domains. MIL-STD-2525C has also been adopted by the NATO and uses a standard format for the following categories of contacts:

- Pending
- Unknown
- Friend
- Neutral
- Hostile
- Assumed friend
- Suspect

Extrinsic symbol modifiers have been defined that may be added to the primary object icon. These extrinsic modifiers conform to the template shown in Figure 3-2. Modifiers have been developed for each of the following geospatial or application domains:

- Unknown
- Space
- Air
- Units
- Equipment
- Installations
- Sea surface
- Sea subsurface
- Special operations forces

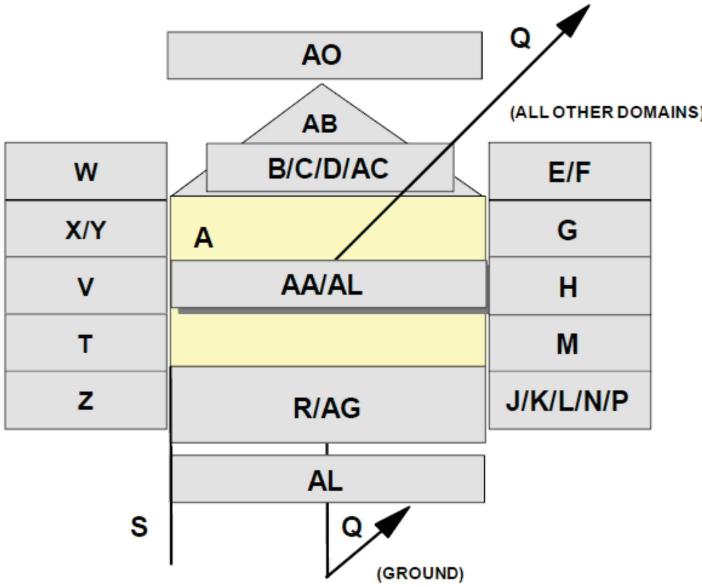


**Figure 3-2: General Layout of Military Symbology**
**Image reproduced from MIL-STD-2525C (DOD, 2008)**

Each letter or letter combination indicates an elaborating 'field' of associated information. Of these letter or letter combinations, two are concerned with uncertainty. J is an evaluation rating concerned with reliability of the information and credibility of the source; an extrinsic graphic may be applied around the symbol indicating uncertainty various object attributes as shown in Figure 3-3. Further to this, the textual label 'unknown' may be applied to make uncertainty explicit.

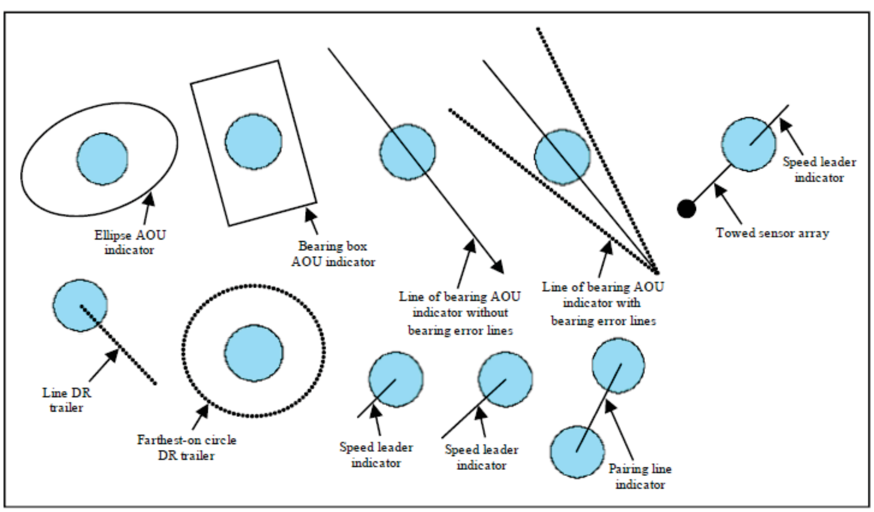


**Figure 3-3: Extrinsic modifiers showing techniques for displaying attributes and uncertainty of the primary object icon (blue filled circle).**
**Image reproduced from (DOD, 2008).**

As an intrinsic example of representing information, the various object symbols for sea surface track contacts are provided in Figure 3-4. Contacts are distinguished both by shape and colour; the text labels were added to the symbols for this report to identify the icon representation.


**Figure 3-4: Sea surface contact symbols showing extrinsic icon representations. The text labels are added for illustration purposes only. Icon images reproduced from MIL-STD-2525C (DOD, 2008)**

The examples above, while making explicit reference to uncertainty, they do so qualitatively and do not explicitly express the magnitude temporal or geospatial uncertainty. Indeed, MIL-STD-2525C make no mention of geospatial uncertainty and leaves the specific depiction of graphics associated with areas of uncertainty and the calculations associated with them up to the national authority and those developing military tactical displays.

## 3.3 Royal Canadian Navy

### 3.3.1 Data Fusion

The RCN has a modern Command and Control (C2) system that includes a tactical plot that is among the most capable of allied C2 systems. Of particular interest is the data fusion capability resident in the Combat Management System (CMS) 330 and the associated graphics. The CMS 330 includes a sophisticated data fusion system that currently combines sensor information for the purposes of unambiguously locating contacts in the tactical environment and providing initial identification based on kinematic information. Eventually the data fusion engine will incorporate intelligence information and other databases to amplify the identification and, ultimately, infer the intent of the contact through pattern matching and other artificial intelligence methods.

From interviews with RCN operators, the key sensors that contribute to the data fusion solution are radar, the Automatic Identification System (AIS) and tactical data links[16] (i.e. tracks that are provided from allied ships through link systems such as LINK 16). Other sensor information is also fused, for instance electronic warfare bearings and acoustic information. The data fusion engine integrates geospatial data to provide an instantaneous contact position and speed.

Some sensors are known by operators to be more or less reliable. Accordingly, operators will adjust the priority of some contributing sensors to give them lower priority in the data fusion solution and, in some situations, may remove a sensor from a data fusion solution entirely. The relative priority of sensors in the data fusion solution is incorporated into a Dempster-Shafer theory-based calculation that assesses the degree of belief in the information from one sensor. The fusion algorithm then combines that degree of belief with those for all other sensors before calculating the geospatial position of the contact.

[16] http://en.wikipedia.org/wiki/Tactical_Data_Link

Nevertheless, there is no representation of uncertainty in the resulting contact location. A contact symbol, similar to that shown in Figure 3-4, is provided at the location of the contact as determined by the system. Uncertainty is only indicated to the operator when different sensor information is not automatically fused. In this situation, two or more nearly-coincident contact symbols will be displayed. In this case it is up to the operator to manually decide the most reliable contact track and then merge other symbols with it, a process referred to as ‘correlating contacts’. In this case, there is no averaging of the geospatial information.

### 3.3.2 Tactical Graphics

Modern tactical sensors used in surface and air warfare domains provide reliable and accurate information, such as position or velocity, for sensed objects. However, there can be a great deal of uncertainty in the underwater domain due to the way an acoustic signal (based on pressure) interacts with the water and sea bed features. For this reason there have been a number of graphics developed for the Anti-Submarine Warfare (ASW) team to help them manage the tactical picture. The following Tactical Decision Aides (TDA) were developed for the CMS330 and the images are reproduced from a report prepared during work on modernization of Canada’s Halifax-class frigate (CAE, 2011):

- Water Space Management: this tool deconflicts underwater operations where there is inherent uncertainty in the location of the subsurface assets.

- Torpedo Threat Reckon: this tool displays a graphical object based on a sensor ‘glimpse’ of a torpedo that proceeds toward the ownship on a specified bearing at a specified speed; note that a similar TDA is available for missiles that may be glimpsed before travelling in ways to evade detection – see Figure 3-5.

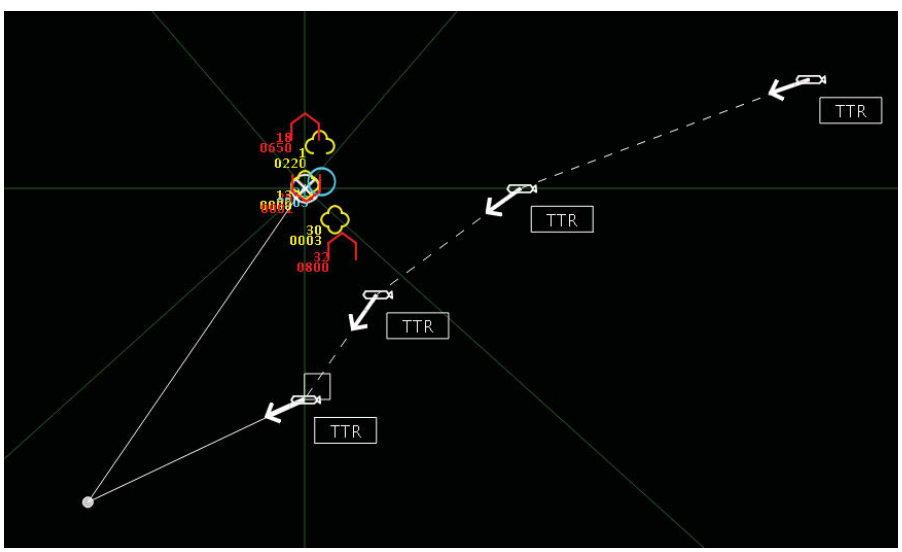


**Figure 3-5: Torpedo Threat Reckon**

- Acoustic Cross Fix: this tool will plot a location of the source along with a shaded area defined by the calculated margin for error on the sensor based on two or more acoustic bearings – see Figure 3-6).

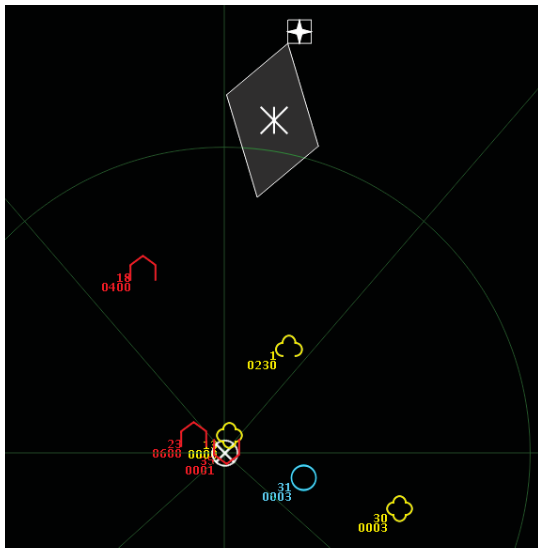


**Figure 3-6: Acoustic Cross Fix**

- Target Motion Analysis: this tool uses successive acoustic sensor readings to develop an accurate location, course and speed for a submarine – see Figure 3-7.

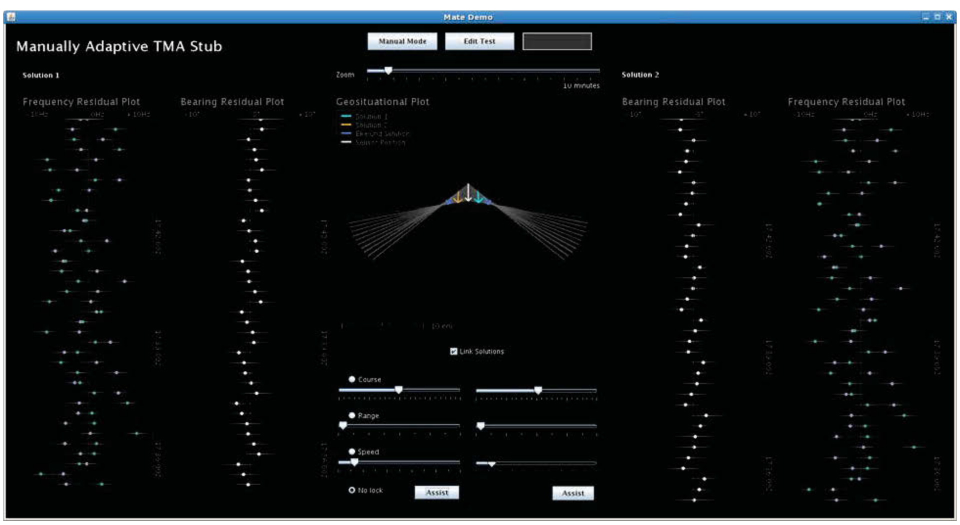


**Figure 3-7: Target Motion Analysis Display**

- Limiting Lines of Submerged Approach (estimates the possible firing position of a submarine)

- Furthest On Circle (estimate the distance a surface or submerged target has travelled since its last detection)

- Cone Of Courses (indicate the most likely area to search for an approaching submarine, given the last known position of the submarine)

**NOTE** that these last three TDAs result in a graphical object and involve the fusion of different sensor information with some inputs from the operator to generate that graphical object. The uncertainty is depicted by an area around the contact (e.g. similar to Figure 3-6); although this does not apply to the Torpedo Threat Reckon or the Target Motion Analysis output.

## 3.4 Private Industry

A search of the internet uncovered few companies that are specifically in the business of developing data fusion graphics. Rather, companies who develop graphical applications claimed to incorporate data fusion engines. This made it very difficult to identify companies of direct and clear relevance to this work. No companies made specific claims concerning the development of graphical methods for representing uncertainty in data fusion graphics. Where research and examples were found, however, was in the area of meteorological prediction of storm tracks and similar applications. Their level of precision is similar to the 'Furthest On Circle' and 'Cone Of Courses' TDAs described above.

It is known from other work that military combat systems integrators develop tailored graphics solutions for tactical displays. For this reason, the largest systems integrators: Lockheed Martin, Thales, British Aerospace (BAe), SAAB, General Dynamics, and Rheinmetall, were all used in keyword searches with the terms 'uncertainty' and 'graphic' in the hope that trade papers would be found. Unfortunately almost all returns concerned business or climate applications. When the organization names were searched with 'data' and 'fusion' more relevant results were returned, but these dealt with algorithms and processing required to achieve data fusion rather than how to graphically present the results.

### 3.4.1 OODA Technologies

OODA Technologies[17] was considered for their expertise in representation of uncertainty in data fusion graphics. OODA is located in Montreal and provides services for, amongst other things, visualization to help organizations understand and navigate data. Their website includes a number of project examples, including several with potential relevance for uncertainty visualization in data fusion graphics.

- RISOMDA is concerned with the development of Maritime Situation Awareness (MSA) products to support wide area surveillance for ship approaches to Canada through the Pacific, Arctic and Atlantic oceans. This work includes integrating a variety of sensor data and has included studies of user trust in the data model, a key component of data fusion and once closely related to uncertainty.

[17] https://ooda-staging.herokuapp.com; www.ooda.ca

- BullBear is a commodity trading application for financial purposes. In common with geospatial data, the BullBear application incorporates information from a variety of sources (generally text-based news articles) and then assigns a score to the commodity. The score (BullBear Index) is the average of all other indexes computed from all sentences in the last 20 relevant news articles for the previous two weeks. This averaging is conceptually similar to the data fusion approach in the CMS330.

- PASE (Persistent Active Surveillance of the Exclusive Economic Zone) fuses radar with AIS information based on track kinematics and geospatial information. There is no mention of whether uncertainty is dealt with although it is expected that an averaging approach to location is used and no uncertainty is represented to operators.

OODA Technologies actively publish their work in a variety of media.

### 3.4.2 Menya Solutions

Menya Solutions[18] was considered for their expertise concerning data fusion and visualization of uncertainty. Menya Solutions is based in Sherbrooke, QC and focuses on automating and supporting real-time decision making in complex environments. Their solutions fall into two main categories:

- Automated behaviour recognition, machine learning and complex event processing.

- Simulation and planning. This involves the modelling of a work domain and simulating scenarios stochastically to generate a repertoire of case based reasoning exemplars.

The Menya Solutions' website includes several project examples with potential relevance for uncertainty visualization in data fusion graphics:

- ICOR is an application for understanding events as they occur in real-time. Sensor data is collected and combined with spatial and temporal relationships among contacts to permit pattern recognition, goal (of the contact) recognition, plan recognition and threat recognition. There is no description of how this information is presented to the operator, if at all.

- SimPlan is a decision support and optimizer tool for simulations.

Menya Solutions recently won a contract with DRDC Valcartier to work on the Naval Battle Management Command and Control Decision and Collaboration Support project with the specific objective of developing the RCN capability in Integrated Air and Missile Defence (IAMD). A current variant of what will eventually be delivered from this work is in service as an integral part of the CMS330.

[18] http://menyasolutions.com/

### 3.4.3 Uncharted

Uncharted[19] (formerly Oculus Info Inc.) were suggested by DRDC scientists. Uncharted develops tools for analyzing data. Uncharted has both planning and real-time applications that have been applied to defence and intelligence applications. Uncharted's product GeoTime represents events spatially and temporally, allowing the analyst to animate the visualization and see how events have unfolded over time. This allows patterns and trends to be identified and studied.

Although most of the applications listed by Uncharted seem to be retrospective analysis, Uncharted does list 'GPS and Location-Based Services (Emergency, Asset Tracking)' as one application, which could be considered analogous to real-time sensor tracking. A .NET Application Program Interface (API) exists that may allow GeoTime to incorporate real-time sensor data (e.g. radar, AIS). GeoTime is also compatible with ArcGIS, which further enhances the ability to fuse a tactical picture with underlying geographical chart information.

While GeoTime has not been used for real-time sensor data fusion, it has been used for intelligence data fusion on the basis of pattern search and temporal link analysis. However, their website does not make any reference to uncertainty in their representations.

Uncharted also have a long list of publications with some having relevance to the visualization of uncertainty for data fusion graphics:

- Wright, W. & Dupuis, C. (1997). Resolving Radar Ambiguities: A 3D look at EW Analysis. Journal of Electronic Defence, Sept.
- Wright, W. & Kapler, T. (2002). Visualization of Blue Forces Using Blobology. In International Command and Control Research and Technology Symposium (ICCRTS), June.
- Kapler, T. & Wright, W. (2002). Visualization of Self-Reporting Contacts for Command and Control. In International Command and Control Research and Technology Symposium (ICCRTS), June.

[19] http://uncharted.software/

# 4 GENERAL DISCUSSION

Almost 20 years ago, Andre and Cutler (1998) observed that it was a generally held view that it is important to consider uncertainty in aviation decision making but that little research had been done on how best to incorporate uncertainty in displays of information relevant to navigation tasks. That insufficient foundational research has been done was restated by Riveiro (2007) almost ten years later and while some progress has been made since Andre and Cutler's time, the issue is still appears to be unresolved (Bisantz, 2013). What is interesting is that few question Andre and Cutler's premise that visualizing uncertainty is important (see Harrower, 2003, for a discussion of this point.) It is interesting that so few of the systems in use or their manufacturers describe capabilities for displaying data uncertainty.

In the papers reviewed for this tasking, the need for visualization was often stated but often only justified in rather vague terms. Perhaps the authors possessed an implicit understanding of the underlying goals and tasks, but the tasks and associated goals for operators in the Maritime defence and security, as described in a variety of Hierarchical Task Analyses, did not seem to explicitly document the need to represent uncertainty. Nor was a Cognitive Work Analysis reviewed that delved into the constraints and decisions these operators faced. Some insight into this problem space may be available reports by Matthews and colleagues (Matthews, Webb, & Bryant, 1999; Matthews, Webb, & Keeble, 2002; Matthews, Webb, & Woods, 2001), however, there was insufficient time to review these documents. Nevertheless, discussions with CAE personnel who had relevant experience was CAF operators in the Maritime defence and security domain acknowledge that uncertainty information was useful during tactical decision making.

Avram (2012) notes that a great deal of sensor fusion visualization research is on anomaly detection, which is generally considered part of high level information fusion (HLIF) involving temporal-geospatial data as well as meta-data. Anomaly detection in the Maritime defence and security domain typically focusses on trying to identify vessels that are behaving in an unusual manner compared with lawful vessels operating in the area – an applied case of target detection among distractors. Anomaly detection is a complex problem, often involving many vessels that may be observed by different sensors in a distributed network leading to different levels of accuracy or timing. Further, there are many situations where behaviour may be anomalous yet lawful (ill-defined problem space.) However, HLIF tasks typically require understanding of temporal-spatial information resulting from LLIF tasks, but exactly how these data are used by domain SMEs is unclear from the papers reviewed here.

# 5 RECOMMENDATIONS

The following recommendations are intended to help clarify how depiction of temporal or geospatial uncertainty can be effectively displayed to Maritime defence and security operators. Some of the information may already exist in documents that were not reviewed or even identified.

1. Identify or establish an explicit description of the goals and activities of Maritime defence and security decision makers at various levels of command that require temporal-geospatial information. This should include a description of the information requirements, in particular the sources of uncertainty, the nature of the uncertainty (i.e. whether it is intransient knowledge or moment-by-moment, case-by-case.) This should also establish unequivocally that operators can use uncertainty information effectively in their reasoning and decision making independent of the method of providing the uncertainty information.

2. Identify or establish through a CWA the constraints imposed on the display of sensor fusion data that might affect an operator's ability to use the information if the data is available to be displayed. This should identify the Human Factors constraints that affect visualizing temporal or spatial data based on psychologically established perceptual and reasoning capabilities. This work could consider multi-modal information displays that are consistent with the constraints imposed by the operational domain.

3. Select or develop an extrinsic or a combined extrinsic and intrinsic approach using techniques that have been shown to be effective for depicting secondary information such as uncertainty, then experimentally validate their effectiveness for improving performance in an application context that suggests comprehension of primary data uncertainty from sensor fusion is advantageous. This should also incorporate a measure of operator control over the display of uncertainty information and how best to implement such control in an operational setting.

# 6 CONCLUSION

This review of the scientific literature and industry state of practice suggests that work remains to be done to establish how uncertainty should be indicated on Maritime defence and security graphical displays of fused sensor data. Although some fundamental information of how operators perceive displayed information exists, refinement of that understanding should be undertaken to establish which methods are feasible and effective from a Human Factors perspective.

Also, the need for visualization of uncertainty in defence information displays needs to be established based on CWA assessment of the domain constraints and on HTA assessment of the operators goals or objectives that are supported by scientifically sound operational effectiveness analyses.

In the interim, a simple, extrinsic indication, or a combined extrinsic and intrinsic indication, of primary data uncertainty that is under the operator’s control would seem to be the most promising approach to ensure comprehension while limiting clutter.

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# 8 DEFINITIONS

The following definitions were adopted by the authors to have a shared understanding of this call-up's objectives. The definitions are derived from those found in the public domain either as formal definitions, such as the U.S. Department of Defense Data Fusion Subgroup, or as informal refinements of colloquial expressions used in reports by other authors in published reports.

## 8.1 Contact

A contact is a physical object or a sensor indication of an object that may be of interest to an operator. In a Maritime domain, contacts typically comprise ships, boats, submarines, airplanes or helicopters, but may also include wildlife or erroneous sensor indications of a physical object.

## 8.2 Colour[20]

Colour is a property of an object that is perceived visually due to emitted or reflected light. There are numerous factors that can affect colour, but it is chiefly determined by hue, saturation and lightness.

## 8.3 Data and Information

Data and information are subtly different concepts with information usually implying some form of processing or organization of data. This distinction seems unnecessary in the current context and the two words will be used interchangeably.

## 8.4 Geospatial

Geospatial refers to the geographical coordinates (latitude, longitude, altitude, depth) used to locate a contact in the AOR.

## 8.5 High Level Information Fusion

High level information fusion (HLIF) is generally considered to be the process of consideration and integration of abstract information that is important to understanding a tactical situation, inferring a threat from contact behaviour or predicting implications for the tactical situation (Blasch, Valin, Jousselme, Lambert, & Bosse, 2012).

## 8.6 Hue

Hue is an attribute of perceived light that is commonly referred to as colour and often categorized by the stimulus similarity to pure red, orange, yellow, green, blue, indigo or violet.

[20] Definitions related to colour attributes were paraphrased from http://www.workwithcolor.com/color-properties-definitions-0101.htm and Wikipedia.

## 8.7 Lightness

Lightness is the degree to which a colour hue is modified by adding a quantity of either black or white. Lightness is commonly referred to as tints (when white is added) or shades (when black is added.) Lightness is sometimes confused with brightness, which is a characteristic the amount of light being emitted or reflected by an object (i.e. luminance.)

## 8.8 Low Level Information Fusion

Low level information fusion is generally is generally considered to be either the process of integration of raw electronic or digital sensor signals into human-interpretable data or the consideration and integration of such interpretable data into information that supports target classification, identification or tracking (Blasch et al., 2012).

## 8.9 Operator

For the purposes of this report, an operator is considered to be a person who uses a visual display of information to manipulate the data, reason about the data or make decisions based on the displayed information. In the tactical Maritime context, operators may be any of the following:

- TACCO – Tactical coordination officer (Maritime aviation: Sea King, Cyclone);
- TACNAV – Tactical navigator (Maritime aviation: Aurora);
- NESOP – Naval Electronic Support Operator (Navy: HALIFAX-Class Frigate);
- NCIOP – Naval Combat Information Operator (Navy: HALIFAX-Class Frigate);
- SWC – Surface Weapons Controller (Navy: HALIFAX-Class Frigate);
- ASWC – Anti-submarine Weapons Controller (Navy: HALIFAX-Class Frigate); and,
- ORO – Operations Room Officer (Navy: HALIFAX-Class Frigate).

## 8.10 Recognized Maritime Picture

The RMP is the presentation of geo-located contacts on an electronic map display intended to allow management of information derived from an array of sources (including sensors) and support tactical decision making (Lapinski, 2010).

## 8.11 Saturation

Saturation is a property of perceived light that indicates the level of pure colour (100% saturation) in a mixture with pure gray (0% saturation).

## 8.12 Sensor

A sensor is a physical device that is capable of measuring some physical property of an object of interest. Sensors that are relevant to the current review for the Maritime domain include:

- Acoustic (sonobuoy);
- Automatic Identification System (AIS);
- Electro-optical;
- Electronic Support Measures (ESM);
- Infra-red (optical);
- Long range identification and tracking (LRIT);
- RADAR (imaging, fire control, long range, short range, weather);
- Satellite imagery; and,
- Traffic collision avoidance system (TCAS).

## 8.13 Sensor fusion

Sensor fusion has been defined a number of ways[21], no doubt varying depending upon the context in which the author was applying the term. The U.S. Department of Defense, Joint Directors of Laboratories (JDL) created a formal definition in the mid-1980s that is frequently referred to, but extensions have been proposed over the intervening years (Foo & Ng, 2013; David L Hall et al., 2001; Steinberg & Bowman, 2001, 2004).

Fusion Levels 2 through 5 of the 6 levels of the JDL Data Fusion Information Group22 (DFIG) model support higher level reasoning and decision making. Although these information fusion levels are generally involved with more abstract information, they have their own associated uncertainty and visualization requirements. Conversely, Fusion Level 0 – Source or signal preprocessing – is involved with the processing of the raw electronic or digital sensor signals that produce the information presented to the operator. This information is usually presented graphically (e.g. an acoustical gram), symbolically on a tactical plot, or as alpha-numeric information that accompanies the graphical plot.

The current work is focussed on Level 1 – Object Assessment – although there is some overlap with both Level 0 (Source preprocessing) and Level 2 (Situation Assessment). Level 1 fusion is concerned with correlating the contact level indicators or signs to merge redundant symbols, localize the resultant object (geographical coordinates, altitude/depth, speed, heading, range,

[21] http://net.cs.uni-bonn.de/wg/sensor-data-and-information-fusion/what-is-it/sdf-definitions/
[22] http://en.wikipedia.org/wiki/Data_fusion

bearing, time of observation) and identify it uniquely so that the contact can be further processed or reasoned about in subsequent situation assessment activities[23]. Results of the Level 1 fusion process are increasingly shared among networked operators who are attempting to construct a common understanding of the tactical environment for an entire task force.

## 8.14 Tactical situation display

The tactical situation display (TSD), also referred to colloquially as the tacplot or tactical plot, is a computer generated map showing the locations and associated textual information for contact contacts in an area of interest.

## 8.15 Time-late

Time-late is an expression used to indicate the recency of information. It is used to refer to the elapsed time between the observation and the time the information is being considered, usually the current time.

## 8.16 Uncertainty

Uncertainty may comprise a number of different concepts including error, ambiguity, incompleteness or deception. Uncertainty indicates a lack of reliability of a nominal value. While uncertainty has implications for the concept of risk, uncertainty is distinct from risk, most notably as it does not entail a concept of loss, injury or adverse consequences. Uncertainty may be represented as a numerical probability, but it can be indicated graphically as a categorical representation, such as a probable location area versus an improbable location area for a contact on a tactical map plot.

Within the context of this document, uncertainty is considered to be the counterpart of accuracy and reflects the possible variability of a datum about its nominal value. More specifically, this report is concerned with the variability associated with the nominal values of a contact's attributes (i.e. latitude, longitude, et cetera) and recency of the observation.

Zuk (2008) presents an extensive typology for describing uncertainty that may be used to identify contributing factors associated with the reliability of information. But, while it may be important to be able to deconstructed fused information through the use of data fission tools, it is not clear that it is necessary to visualize separate contributions of uncertainty to denote the reliability of the primary data sign or icon.

## 8.17 Visualization

The Oxford dictionary[24] defines the verb "visualize" to be 1. To form a mental image (of something); to imagine (something); and 2. To make (something) visible to the eye. The current review involves both of these definitions as it is focussed on visual display techniques intended

[23] http://defensesystems.com/articles/2009/09/02/c4isr1-sensor-fusion.aspx
[24] http://www.oxforddictionaries.com/definition/english/visualize

to support the operator’s understanding of the location of contacts within the AOR over time (past, present and future.)

# 9 ACRONYMS

| | |
|---|---|
| AIS | Automatic Identification System |
| AOR | Area of operations |
| API | Application Program Interface |
| ASW | Anti-Submarine Warfare |
| C2 | Command and Control |
| CAF | Canadian Armed Forces |
| CMRE | Centre for Maritime Research and Experimentation |
| CMS | Combat Management System |
| CTFG | Canadian Tracking and Fusion Group |
| DND | Department of National Defence |
| DRDC | Defence Research and Development Canada |
| DTIC | Defense Technical Information Center |
| ETURWG | Uncertainty Reasoning Working Group |
| FACTS | Future Area Control Tools Support |
| GPS | Global Positioning System |
| HFM | Human Factors and Medicine |
| HLIF | High Level Information Fusion |
| HTA | Hierarchical Task Analysis |
| IEEE | Institute of Electrical and Electronics Engineers |
| InfoVis | Information Visualization |
| ISIF | International Society of Information Fusion |
| LLIF | Low Level Information Fusion |
| NATO | North Atlantic Treaty Organization |
| NASA TLX | National Aeronautical and Space Administration Task Load Index |
| PDF | Portable Document Format (Adobe®) |
| PPD | Potential Problem Display |
| RCN | Royal Canadian Navy |
| RMP | Recognized Maritime Picture |
| RTO | Research and Technology Organization |
| SAR | Search and Rescue |
| SAS | System Analysis and Studies |
| SciVis | Scientific Visualization |
| SET | Sensors and Electronics Technology |
| STO | Science and Technology Organization |

| | |
|---|---|
| Tacplot | Tactical plot |
| TDA | Tactical Decision Aides |
| TSD | Tactical Situation Display |
| VAW | Vertical Assistance Window |

# APPENDIX A ANOTATED BIBLIOGRAPHY OF RELATED DOCUMENTS

The following documents were reviewed and while they did not have information that was directly applicable to the central issue of uncertainty visualization of geospatial data, they did contain associated information that the client expressed some interest in. For that reason, the documents are included in this appendix with notes taken by the reviewers.

**Atrey, P.K., & Hossain, M.A. (2010) Multimodal fusion for multimedia analysis: a survey. Multimedia Systems, 16:345-379**

This paper is intended to provide multimedia researchers with a state-of-the-art of fusion strategies that are used for combining multiple modalities in order to accomplish various multimedia analysis tasks. The authors classify the multimodal fusion research literature by the fusion methodology and the level of fusion. For each method, the paper describes the basic concept, identifies advantages and weakness, and notes some applications.

The authors categorized multimodal fusion approaches as one of three types with subdivisions:

1. Rule-based fusion methods
    a. Linear weighted fusion (widely used)
    b. Majority voting
    c. Custom-defined rules (flexible)
2. Classification-based fusion methods
    a. Support vector machine
    b. Bayesian inference (easy to extend but brittle)
    c. Dempster-Shafer theory
    d. Dynamic Bayesian networks (DBN; applied to time-series data)
    e. Neural networks
    f. Maximum entropy model
3. Estimation-based fusion methods (localization and tracking tasks)
    a. Kalman filter
    b. Particle filter

**Zuk, T. (2008). Uncertainty Visualization. Presentation at the InfoVis – Winter 2008.**

This is a Power Point Presentation introducing a group of methods used for uncertainty visualization although data fusion is not the focus in this presentation. This presentation provides an uncertainty typology, including accuracy/error, precision, completeness, consistency, lineage, currency/timing, credibility and interrelatedness.

The presenter identified four types of uncertainty visualization approaches that consist of taxonomic approach, semiotic, perceptual and cognitive theory, as well as human factors and task constraints. For the taxonomic approach, the presenter defined four types of attributes/data, including datum values, location of the datum, visualization axes mapping and extend of both location and values.

The author of the presentation identified seven methods of encoding for uncertainty visualization: (1) add glyphs, (2), add geometry, (3) modify geometry, (4) modify attributes, (5) animation, (6) sonification, and (7) psycho-visual. For the semiotic approach, the author introduced five representation methods, e.g. crispness, resolution, transparency, virtual reconstructions and molecular positional uncertainty.

Some key points relevant to human factors of visualization and decision making were showed in the slides, including heuristic evaluation, local contrast affects, colour and gray perception. The author also introduced the Bayesian theorem for evidence-based diagnosis. The author listed some future directions for uncertainty visualization, including providing support for cognitive task simplification, supporting emphasis and de-emphasis of uncertainty information, supporting viewing of uncertainty as metadata and as separate data, allowing the user to select realizations of interest, mitigating cognitive heuristics and biases with reasoning support, providing interaction to assist knowledge creation, and assessing the implications of incorrectly interpreting the uncertainty.

The presenter showed 6 images for the representation for uncertainty: (a) vector fields, (b) temporal uncertainty in Archaeology, (c) crispness, (d) resolution, (e) transparency, (f) virtual reconstructions, and (g) molecular positional uncertainty.

**Blasch, E.P., Dorion, E., Valin, P., Bosse, E., and Roy Jean. (2010). Ontology Alignment in Geographical Hard-Soft Information Fusion Systems. Proceedings of the 13th Conference on Information Fusion (FUSION 2010).**

This paper explores issues of fusing hard and soft data, suggesting a growing need for alignment of both (1) exploited physical imagery products and (2) derived ontological textual labels (semantic markup). The authors first reviewed ontology research for situation awareness, information fusion and surveillance, and then focused on hard-soft fusion, hard-soft ontology fusion and geospatial ontologies.

They proposed an example of hard-soft ontology on Geographical Information System (GIS) to demonstrate the need for ontology alignment to assist uses for pragmatic surveillance. The authors identified hard data as the data from physical sensors (e.g., images), and soft data as the data from semantic markup (e.g. textual labels).

The ontological fusion example proposed in this paper consists of two information systems applied in a Maritime scenario, each of which collect and label their products uniquely. The authors indicated the need to align (or match) the ontology representations of the physical objects to the situation for coordination with the image displays of the coastal areas (e.g., determining 'land areas' and 'waterways', traffic patterns, types of vessels, and vessel activities and identification by a way of associated behaviors and class labels from historical data).

**Fischer, Y. and Bauer, A. (2010). Object-Oriented Sensor Data Fusion for Wide Maritime Surveillance. Proceedings of the 2010 International Waterside Security Conference (WSS). IEEE.**

This article introduces an object-oriented approach for the fusion of observations produced by heterogeneous sensors. The authors reviewed related work, in particular, Endsley's perception-comprehension-projection theory and the Joint Directors of Laboratories data fusion information model, and proposed an object-oriented architecture that was implemented and tested with the STEP Scenario Simulation Tool.

The proposed architecture, known as Object-Oriented World Model (OOWM), comprises an Instance manager, a Data Association, a Fusion Manager for position/speed, and length, and a Classification module. The Observation Interface connects with various sensor services through an observation bus and an access Interface is provided for application-level event reports or queries for fusion results. A simple rule-based approach is included in the architecture for situation awareness services.

**Khaleghi, B., Khamis, A., and Karray, F. O. (2013). Multi-sensor data fusion: a review of the state-of-the-art. Information Fusion, 14(1): 28-44.**

This paper presents a comprehensive review of the data-fusion state of the art, exploring its conceptualizations, benefits and challenging aspects, as well as multi-sensor data fusion algorithms. They note that uncertainty in the products of multi-sensor data fusion may arise due to any of the following:

- imperfect data
- correlated data
- inconsistent data
- disparate data
- Incomplete data

For the fusion of imperfect data, the authors summarized the algorithms as follows:

- Probabilistic fusion (Bayesian fusion is the core method)
- Evidential belief reasoning (Dempster-Shafer theory is the popular method)

- Fusion and fuzzy reasoning
- Possibilistic fusion using fuzzy-set based possibility degree for data fusion
- Rough set based fusion
- Hybrid fusion approaches, e.g. hybridization of fuzzy theory with Dempster-Shafer theory, and combination of fuzzy set theory with Rough set theory
- Random set theoretic fusion

Two approaches for fusion of correlated data were reviewed:

1. eliminating data correlation
    a. explicitly by removal of data
    b. implicitly through reconstruction of measurements
2. data fusion in presence of unknown correlations
    a. Covariance Intersection is the most common fusion method to deal with correlated data.

The authors reviewed methods for fusion of inconsistent data based on three data types

1. spurious data
2. out of sequence data
3. conflicting data

The majority of work on treating spurious data has exploited Bayesian fusion frameworks to identify or predict spurious data, and subsequently eliminate these outliers from the fusion process. An approximate sub-optimal solution to out of sequence measurement (OOSM) called “Algorithm B” as well as its famous optimal counterpart “Algorithm A” had been proposed. The problem of out of sequence data for disordered tracks (OOST) is solved using equivalent measurements obtained from individual sensor tracks, which are then used in an augmented state framework to compute the joint density of the current target state and the target state corresponding to the delayed data. Two techniques for fusion of disparate data, the Dempster-Shafer theoretic framework for soft/hard data fusion and the human centered data fusion paradigm, are briefly reviewed.